Appendix B

Textiles and Garments for Chemical and Biological Protection[1]

Frank K. Ko

INTRODUCTION

Textiles and garments are important components of the soldier system. They are the soldier's second skin, the barrier between the soldier and the surrounding environment. Although the global and national political climate has changed, and defense concepts and doctrines along with them, the basic role of clothing in protecting the soldier has remained the same.

As the battlefield environment becomes increasingly complex, we need to ask the fundamental question from time to time whether textile and garment manufacturing technology are keeping pace with current and projected demands. Do we have the fiber materials to meet specific needs? Do we have the yarn technology to convert fibers to linear fibrous assemblies? Do we have the fabric formation technology to convert fibers and yarns to planar or three dimensional (3D) fibrous assemblies? Do we have the garment assembly technology to join fabrics together to form chemical-biological (CB) protective garments? Do we have the finishing and coating materials and technology for advanced CB protective garments? Do we have the detection technology to monitor the residual life of the barrier system?
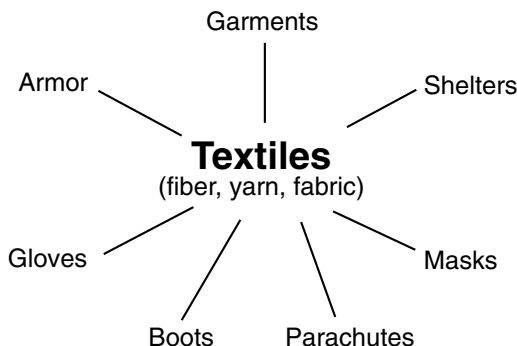

FIGURE B-1   Textiles for the protection of deployed U.S. forces. Source: U.S. Army, 1994.

Textiles are fibrous materials that include natural and synthetic fibers; linear assemblies of these fibers, such as yarn and rope; and two-dimensional (2D) and 3D assemblies of fibers in various fabric forms. These fibrous assemblies constitute the structural backbone of a broad range of military products, including garments, body armor, gloves, boots, shroud lines, masks, and shelters (see Figure B-1).

Military textiles provide battlefield, environmental, physiological, and physical protection (Table B-1). These protective functions are often required simultaneously and must not interfere with each other. For example, a barrier to protect against a chemical warfare agent must be completely impermeable, which interferes with physiological protection requirements that demand permeability to prevent heat stress.

This discussion is focused on CB protective textiles and garments. A review of the literature is followed by a description of the evolution of the requirements for CB textiles and a review of the current CB textile systems. Next, material technology (the current state of fiber, yarn, fabric, and garment technology) is assessed in terms of the nation's readiness. The performance of textile structures relevant to CB protection is expressed in terms of performance maps. On the basis of the requirements and the performance maps, development trends in CB protection are then presented. Finally, the outstanding technical issues are described.

REVIEW OF THE LITERATURE

The published literature in the public domain is limited. Information is scattered in a few chapters, monographs, and mostly in proceedings of workshops and conferences. Morris (1977), for example, summarized the

TABLE B-1 General Requirements for Protective Textiles

Battlefield Protection
    Chemical agent barrier
    Flame-resistance
    Thermal-radiation protection
    Ballistic protection
    Camouflage
    Low noise generation

Environmental Protection
    Insect proof
    Windproof
    Air-permeability insulation
    Waterproof
    Snow-shedding

Physiological Protection
    Minimum heat stress
    Windproof
    Air-permeability insulation
    Moisture-vapor permeability
    Self-sterilizing

Physical Protection
    Durability
    Low weight and bulk
    Resistance to soiling
    Self-sterilizing

Source: Morris, 1997.

requirements and classifications of protective clothing for defense purposes but only briefly discussed CB textiles.

The most relevant summary of the state of CB protective textiles was presented at an Industrial Fabric Association international conference in 1982 at which the threats of chemical warfare were described by Colonel Hidalgo of the U.S. Army Chemical School. He explained how the doctrine that led to the establishment of CB protective concepts (or fundamental principles) was formulated. The fundamental principles are: (1) contamination avoidance; (2) protection (individual and collective); and (3) decontamination (Hidalgo, 1982). These same concepts largely define the U.S. CB protection philosophy today.

Dr. Roy Roth, while working at the U.S. Army Natick Research, Development and Engineering Center (NRDEC) (now called the Soldier and Chemical Biological Command's [SBCCOM] Soldier Systems Center at

Natick) outlined the development of requirements and provided solutions and directions. Much of his discussion is still applicable today, and some concepts are just beginning to be implemented. Based on his interpretation of the Army Training and Doctrine Command's battlefield scenario, AirLand Battle 2000, Roth believed that a battlefield CB protective uniform would replace the overgarment concept of the 1970s and 1980s. He then pointed out the shortcomings of activated carbon-based protective garments (e.g., limited field life, as the activated carbon absorbs perspiration, thus depleting chemical agent sorption capabilities). Besides protection by carbon sorption, Roth introduced new concepts, such as chemical decomposition of agents and semipermeable barriers that combine sorption and decomposition.

Roth also discussed the technologies for implementing these concepts through textile materials. He focused especially on the development of multifunctional fibers, yarns, and fabrics engineering, which has led to new engineering technologies, especially melt-blown nonwoven fabrics. He also introduced the notion of a generic type of uniform for the joint service of the Army, Navy, and Air Force, which led 15 years later to the current joint service lightweight integrated suit technology (JSLIST) uniform (Roth,1982).

At the same conference, Mr. Vachon of ILC raised the issue of availability and cost of fibrous material from the contractor's point of view. He pointed out that heat stress was a problem with the microporous Teflon film, as well as the long cycle time for testing and product qualification.

To remedy the lack of research in CB protective textiles during the 1970s, several research programs were initiated by NRDEC in the 1980s. For example, to evaluate the effect of fiber architecture on the transport properties of garments, a three-year study was contracted to the Textile Research Institute, under the direction of Dr. Bernie Miller. This program resulted in a new experimental technique based on the finding that the liquid breakthrough resistance in fabric structures could be optimized by symmetric design of the fabric surface (Miller, 1986).

Considering the importance of fabric structures in CB protection, NRDEC also contracted with Drexel University, under the Textile Center of Excellence Program, to carry out a study on the feasibility of improving the performance of CB protective textiles by fabric engineering. The Drexel study revealed that the transport properties of a fabric could be engineered by modifying fabric construction, yarn materials, and yarn geometry and that a lighter and more air-permeable fabric could be designed and fabricated than the current 50/50 nylon/cotton shell fabric without sacrificing mechanical properties. Because of the lack of a quick and accurate testing method for liquid/vapor penetration, the effectiveness of the experimental fabrics for CB protection could not be tested (Ko and Geshury, 1997).

As part of the NRDEC/Drexel Textile Center of Excellence Program, an update of current CB protective concepts was presented in the 1996 Workshop on Chemical Protective Textiles jointly organized by NRDEC and Drexel University (Ko and Song, 1996). The topics covered in this workshop included barrier mechanisms for liquid and vapor agents; the characterization of barrier effectiveness based on liquid transport properties; modeling the interaction of fabric structure and physiological responses; a review of textile materials and structures for chemical protection; water and oil repellents; design of chemical protective textiles; design of chemical protective clothing; human factors in protective clothing design; and reactive systems for protection and decontamination. The workshop concluded with a projection of future protective systems and the announcement by Dr. Donald Rivin of NRDEC of the JSLIST preplanned product improvement (P3I) program.

Other sources of information on CB protective textiles are the proceedings of a series of workshops sponsored by the American Society for Testing Materials (ASTM) (McBriarty and Henry, 1992) and the ASTM special technical conference series. The ASTM articles tend to focus on test methodologies and are concerned primarily with protection in industrial environments. The Scandinavian Symposium on Protective Clothing, held every other year, covers a broad range of topics related to CB protective textiles. The role of nanotechnology in soldier protection was discussed in a recent Army workshop in Boston (Gibson and Reneker, 1998). Nanofiber structures and various reactive polymers can now be tailored for specific forms and functions.

The Army Research Office, along with other Army laboratories, has started a multidisciplinary university research initiative (MURI) involving researchers from North Carolina State University, the University of Akron, and Drexel University. Although the topics are basic in nature, the emphasis is on CB and ballistic protection.

In summary, research in CB protection textile technology was quite limited until the early 1980s when the threat of CB warfare from the Soviet bloc spurred research and development (R&D) in CB textiles and led to the development of the JSLIST garment. Considerable R&D (mostly developmental) is being conducted in the private sector, mainly on the agents and environments in industrial environments, which differ markedly from those encountered by ground soldiers. The most closely related industrial research is on protection from agricultural pesticides, which are somewhat similar to nerve agents. No significant breakthroughs in CB protective textiles are expected until new multifunctional fiber materials in a broader range of dimensional scales and structural geometries are available in an integrated design for manufacturing environments.

HISTORICAL DEVELOPMENT AND REQUIREMENTS FOR CB PROTECTIVE TEXTILES

The requirements for CB protective barriers have evolved through the years. This evolution was described in a lecture by Dr. Roy Roth (1982), which includes excellent background on the development of CB protective textiles. The following excerpt is taken from Dr. Roth's lecture:

> In the late 1960's the Army research effort had led to the development of a new biological protective clothing system. At the same time, under the Nixon administration, the government's policy to abstain from use of chemical warfare agents led to significant action. First, although the chemical biological protective clothing developed at the time was adopted by the Army in 1970, no production of the system was authorized. Such research funds as were available were committed to other higher priority projects, with virtually no funds being committed to further research in chemical protective clothing in the years thereafter.

> The clothing system adopted at that time was intended for ground soldiers, and more importantly it was intended to be used essentially in a defensive mode. It was a system that a soldier would use if attacked and which would permit him to move to a safe area. It was specifically not envisioned for use by ground or air combat vehicle crewmen. For most of such applications, the excessive bulk and heat stress provided by the uniform would limit the crewmen's activities.

> In the following seven years from 1970 to 1977, not only was relatively little research conducted in this area, but equally importantly, the battlefield scenario changed significantly. The development of a highly mechanized army employing large numbers of ground vehicles and helicopters de-emphasized the concept of the individual combat soldier covering large amounts of terrain on his own.

> Another change that occurred in this period was the aggressive development of chemical warfare tactics by the Soviet government. In the late 1970s it was apparent that the Soviet bloc nations were mentally, physically and emotionally equipped to use chemical biological agents in offensive modes. There was ample evidence emerging that the Soviets were organically and logistically equipped for this purpose. Down to the unit level, the Soviet army trained with and dispersed its agents, such as to make it obvious that the Soviet forces would be ready, willing, and able to use such chemical biological agents on the battlefield as if they were conventional weapons.

> It was equally clear that in 1977 the US was unprepared for such a situation. It is hard to imagine the nature of the obstacle confronting us in order to turn this situation around, starting with what we had. First there was a realization that chemical biological protective clothing was at best a product with substantial limitations. As noted earlier, it was

designed for defensive operations, and because of its bulk and warmth it was unsuitable for conducting extensive offensive operations, particularly in a warm environment.

We had, as noted, conducted no significant research in this area during the period 1970 to 1977. We had certainly not kept up with the times in terms of extracting what little we could from research and development in the civilian sector. On the other hand, it is an area in which little industrial research is conducted. Perhaps the nearest area of related industry activity is in the agricultural pesticides, many of which are first cousins to the nerve agents in today's military arsenal. However, little effort has been devoted to protecting against such agents in the context of an aggressive ground soldier.

To better appreciate the nature of the technical problems confronting us, we can stand back and attempt to analyze the problem in simple objective terms. Our concern is the human body, which suddenly finds itself in an alien environment comprised of an array of unwanted chemicals which are present in gaseous form, aerosol dispersed clouds, or in liquid and possibly solid form.

The eyes and the oral nasal cavities are readily accessible routes for such materials to enter the body. Some agents may be percutaneous and enter the body at any time they can reach exposed skin. The affects on the body will vary from skin inflammation to attacks on the nervous system. The end effects, depending on the agent, will run the gamut from incapacity to death. The time required to render the soldier ineffective is extremely short.

Between the soldier and a hostile environment we need a barrier, or at least a filter, that will screen out the unwanted agents. A wide variety of materials exist that provide this. However, almost all of them have one or more glaring deficiencies, which rule out their use as clothing items.

In the protective clothing area, the problem is far more complex than the typical materials research problems, which can find their solutions in sciences such as physics, chemistry, metallurgy, and so forth. When we get to clothing systems, the typical materials engineer finds himself confronted with some severe additional constraints. The materials we want must, at the very least, be able to bend and breathe in order to permit movement and avoid heat stress. Moreover, the material must be capable of being mass-produced at a reasonably low unit cost and ideally must be capable of being maintained for extended use in the field.

Among other features, it should include the ability to be camouflage printed, as well as to be laundered and decontaminated ... The material should present the strength, durability and abrasion resistance that we need for clothing in a rugged environment. Since they will be

worn in contact with the skin, there are requirements for tactile comfort and the absence of dermatological affects. Finally, the end items must be capable of withstanding extended storage under a range of temperatures and humidity without degradation.

For the ground soldier the foregoing fills many of the requirements, but for the man in combat vehicles on the ground or in the air, where a flame hazard exists, we must add the additional requirement of non-flammability.

We want to provide a barrier between the man and the environment without simultaneously creating heat stress. This would appear to present a contradiction. We want a material that is on the one hand permeable to air and body moisture vapor, and at the same time we want it to present a protective barrier to unwanted chemicals in any form.

A selective barrier is desirable, and the basic protective overgarment system we adopted in 1970 achieves this by using activated carbon in sorptive matrix to filter out the agents. The carbon is contained in a polyurethane foam matrix, which, unfortunately, carries a number of penalties, not the least of which is the heat stress it produces.

Beginning in 1978 the Natick Laboratories began rebuilding the technical base in this area, while at the same time the Defense Department began production of the CP [chemical protective] overgarments. The development of this production market stimulated interest in the research area as well. A few firms that understood the shortcomings of the current product began to turn their efforts to the problem of producing an improved overgarment material. Because of the nature of the problem and the long period of dormancy of research, we also recognized a need to have industry more completely understand both the perspective and potential that we foresaw, in hopes of stimulating still further research activities.

Within the Department of Defense, it was also recognized that the government would have to support such research, and, by 1979, several complimentary actions had been undertaken.First, Natick Laboratories and the Army Research Office conducted a seminar for industry and academic institutions to describe the problem and the potential needs. Secondly, a combined Defense Department Joint Services Technical Plan was put together with short range, intermediate, and long range objectives. In addition, a formal announcement was published in the *Commerce Business Daily* indicating the Army's initiation of a multi-million-dollar research effort, and approximately twenty-four firms indicated interest in participating in this program. Some are here represented today.

Subsequently in late 1979, eight firms responded with proposals, and research and development contracts were awarded to four major

organizations. In addition, unsolicited proposals resulted in several other contracts being awarded, and the net result was a multimillion-dollar commitment to development of improved chemical protective material.

The response by industry has been heartening, and results to date are very encouraging. While many of the materials that have been produced are still being subjected to live agent testing, there is evidence that a new generation of overgarment materials may be within sight. We expect to extract from the technological base one or more materials to go into field tests in the year ahead.

The Army's Training and Doctrine Command has recently developed the scenario entitled AirLand Battle 2000. This is an attempt to look at the future in terms of the way the Army would operate in the battlefield in the year 2000 while at the same time stimulating the development of new ideas to serve the battle scene. One message that becomes clear is that we will in the future depart from today's concept of an overgarment and will be requiring a battlefield uniform that inherently possesses chemical protection. That places an unusual demand on the garment in terms of extended life in the battlefield and its ability to be maintained by conventional laundering procedures.

Today's CP [chemical protective] materials have a limited field life because a soldier's perspiration will be absorbed by the activated carbon. The greater the number of sorptive sites that are occupied by chemicals in the perspiration, the less the material will be able to absorb unwanted agents.

For this reason, the garment of the future will either have to avoid the use of activated carbon or incorporate means by which the sweat poison mechanism may be defeated or minimized. We believe it is possible to achieve the latter. There are also some signs that future generations of garments may not have to depend on activated carbon.

The overgarment existing today has this configuration: The outer shell consists of the 5-ounce nylon/cotton blended twill, the inner component, the so-called active part which contains the activated carbon impregnated into approximately a 90-mil polyurethane foam, has a liner, two-ounce nylon tricot. The bottom two layers are laminated together, and the top layer essentially floats and is put on as the garment is manufactured.

To do this, you reduce the weight in bulk, stressing again, putting this into a combat uniform configuration as opposed to a defensive mode, increase shelf life, adding fire retardancy as best we can, particularly for tank and air crewmen, and making it launderable. It should be launderable not only in combination with being decontaminated, should there be a threat, but since it hopefully will be the combat uniform it should be launderable during the time that it is being worn when there is no threat . . .

Durability, camouflage, you tend to look at this whole thing, remember Alec Guinness and the man in the white suit. Well, we can't even do that, we have to have camouflaging to go along with it. Water repellency, as I mentioned, perspiration resistance and petroleum products, nontoxic as far as materials go and compatibility with other items, . . . whether they be a backpack or a detection kit and so forth. It must all be compatible with those systems, too.

There are many different material systems being investigated to attempt to achieve these objectives. . . . Some of them are based on active carbon power, some of them are based on active fiber yarn, some of them are based on what I call barrier film.

Perhaps a simpler way of demonstrating the scope of the program is to sort out the various efforts in terms of mechanisms or approaches involved. These are the three broad categories, which comprise the technical approaches that exist right now. Approach one is based on sorptivity, using activated carbon in various forms. Approach two is based on trying to develop and put into a uniform some way of actually destroying the chemical threat by decomposition. Number three, is based on either a combination of the above or individually a barrier of some sort . . . in the first category, based on carbon powder. Instead of the polyurethane foams other possible foams might have advantages, being more permeable, being substantive to the carbon, etc., so that the activity of the carbon may remain higher.

Technology allows us to make hollow fibers into which we could put activated carbon powder. Technology permits us to make fibers *in situ* along with carbon powder. Essentially you would be laying down a web of material. Technology permits putting in carbon powder along with melt-blown materials such as polypropylene. I draw particular attention to . . . what I call the nonwoven area, which I think would have some very interesting possibilities.

From the carbon fiber standpoint, this is also being pursued. In general it is noted or to emphasize the expense increases as we go from powder to fiber and within fiber from staple down to fabric. [There] are different forms of carbon fiber, using staple. It can be done by conventional techniques, putting down either wet laid or dry laid nonwovens. We can flock carbon fiber onto various substrates. We can make engineered fabrics out of carbon yarn either with other materials to strengthen it or in other configurations. We can start with fabrics, which are one hundred percent activated carbon and use it somehow. It is fairly weak and brittle to begin with, so it would have to be protected.

Presently carbon fiber is not available in any reasonable quantity domestically. It is only available overseas (Japan or England), and that is a deficiency. If this approach is successful, we would have to have a domestic source.

The second broad category, protection by chemical decomposition, is not new in concept but is new in terms of materials and technology we are applying to the problem. These approaches may hold an answer to some of the longer range needs. It has been known in the literature that there are materials that can hydrolyze the threats. It has been shown that certain ion-exchange resins will do this. It is a question of how we incorporate them into a fabric, and are they active enough to really decompose the threat during a dynamic situation.

There has been recent publicity about some enzymes that have been isolated primarily from squid, which are known to hydrolyze certain live agents. We have the same question. Is it possible to immobilize these somehow and attach them to fabrics, and if so, will it have all of the other properties that are needed, that were listed earlier?

You begin to think, well, are these possible to launder, to decontaminate, etc. Finally, there are efforts directed to the third approach. It reflects an attempt to combine some of the foregoing approaches by developing an engineered material system. Given the present and expected future threat, representing an array of different agents, such a system would have growth potential, which is necessary given the rapidly changing technological world in which we live.

Ideally, of course, it would be nice to have a semipermeable barrier that will keep out the agents and will breathe, will allow moisture vapor to go through and from a waterproofing standpoint will keep out liquid water. Ideally, as I say, it would be better to have that without the need for an absorptive material.

I think most of the approaches and techniques, which I talked about, can tend to identify here. It is best to go around them again to repeat them, starting with carbon, putting carbon powder again into a textile material, whether it be embedded in the fiber or in a hollow fiber, trying to use carbon fibers in one form or another. Your approach of using reactive materials, whether they be, for example, ion-exchange resins, is more of the idealized situation that I just mentioned as a possibility.

On the next one, the barrier film actually exists right now. That's the composition of the butyl rubber overboot and is the system, which the Soviets have gone toward. Unfortunately, it maximizes heat stress and is completely impermeable, which is not a desirable situation for a combat uniform.

Another possibility is using activated fibers again, laminated structures and the possibility of using nonwovens in one form or another.

The impetus given to this program and the results to date will lead to continued funding of research and development efforts in chemical protection material. From a production standpoint, there is no question

that a significantly improved chemical production uniform would produce in itself a sizeable market.

In the period 1977 to 1981, we procured approximately six million chemical protected overgarments, which cost about $188 million. In time, these garments will have to be replaced, and thus a sizeable market looms ahead. If we had a CP uniform today that could be used as an everyday battle uniform with the requisite field life and ease of maintainability, this would certainly stimulate this process and lead to additional procurement.

. . . [T]he Army, Navy, and Air Force have some specific needs for chemical protection, but it is distinctly possible that a system offering minimum heat stress, which would include flame resistance, would be universally adopted by all services. Also, the possibility of the allied forces incorporating and improved system exists, too.

In previous comments I have addressed the chemical protective uniform as opposed to the other components such as footwear, headwear, and mask. For your information the mask and so forth are the responsibilities of the Chemical Systems Laboratories where the remaining part of the uniform are their responsibility, including the gloves and the overboots of the Natick Laboratories.

The footwear and handwear represent another opportunity in that today's products are impermeable butyl rubber, which in the case of handwear, represents significant problems of loss of tactical sense. There is no question that we want to develop handwear that provides the minimum encumbrances and maximum tactical sense possible. Although much of our effort to date has concentrated on protective clothing, a separate initiative has been undertaken to develop highly tactile gloves. In this area, in which materials research people who have familiarity with the elastomer technology will probably be best equipped to handle this task.

Our current butyl rubber items, I might add, also have a flammability problem, which we wish to avoid in the future. This is another material characteristic that would be desired not only for handwear but also for footwear and hood materials, which cover the head area.

The technical requirements for CB protective textiles described by Dr. Roth, which are summarized in Table B-2, can be further divided into five key properties: weight, bulk, durability (wear time-protection time), comfort, and heat stress. The specific requirements of these properties were quantified in a recent presentation by Mr. Phil Brandler of SBCCOM's Soldier Systems Center (1998), who projected the need for a substantial reduction in weight with the ultimate goals of indefinite wear and self-

TABLE B-2 Requirements for Chemical
Protective Textiles

Reduced heat stress
Reduced weight-to-bulk ratio
Combat uniform configuration
Longer service life
Longer shelf life
Fire resistance
Laundering capability
Decontamination capability
Reusability
Durability
Camouflage capability
Water repellency
Perspiration resistance
Resistance to petroleum products
Nontoxic materials
Compatible with other items

Source: Roth, 1982.

decontamination. Table B-3 summarizes the evolution of the durability and weight requirements of CB protective garments.

CURRENT BARRIER SYSTEMS

The current U.S. Army chemical protective battle-dress overgarment (BDO) is a composite structure consisting of an outer shell, an inner activated-carbon layer, and a liner (Figure B-2). The outer shell consists of 7oz/yd^2 nylon/cotton blend in a twist weave construction; the liner is a lighter (2 oz/yd^2) nylon tricot warp knit structure.

Reducing weight and bulk, improving durability, and reducing heat stress will require assessing the entire inventory of textile materials, including fibers, yarn, and fabric structures. Weight can be reduced by using fibers of lower density and yarn and fabric structures with low packing density. Bulk can be reduced by using smaller diameter fibers with higher packing density. The durability of the garment can be improved with stronger and tougher fibers and improved fabric construction (e.g., optimal interlacing density). To improve fabric comfort or reduce heat stress, the permeability and thermal conductivity of the fiber and structure can be increased. Table B-4 summarizes the general improvements in material properties required to achieve textile design goals.

The individual can be protected against chemical agents by an impermeable barrier or by a selectively semipermeable barrier. Materials that

TABLE B-3 Evolution of Performance Requirements for Protective Textiles

1960s	XXCC3 underwear	7 days wear
		6 hours protection
1970s	Chemical protective overgarment	14 days wear
		6 hours protection
1980s	Overgarment84/BDO	22 days wear
		24 hours protection
1990s	JSLIST	45 days wear
		24 hours protection
2000s	JSLIST P31	60 days wear
		24 hours protection
AAN	ICS	indefinite wear
		self-decontaminating

Source: Brandler, 1998.

create a physically impermeable barrier to chemical agents are also impermeable to moisture. Impermeable barrier materials, such as rubber and coated fabrics, do not allow enough moisture-vapor permeability to be useful. The effective period of use of impermeable barrier materials is very limited because of heat stress. The impermeable barrier approach was used for protective clothing until the mid-1970s. Currently, it is used only for gloves, boots, and other special applications intended for short-time use, such as the suit, contamination avoidance, liquid protection (SCALP), the toxicological agent protective (TAP) outfit, and the self-contained toxic environment protective outfit (STEPO).

The second approach can be either (1) a semipermeable fabric and a sorptive layer that can filter out/decompose chemical agents or

Outer shell
7 oz/yd² nylon/cotton blended twill (woodland camouflage) with water repellency treatment

Sewn

Laminated

Inner layer
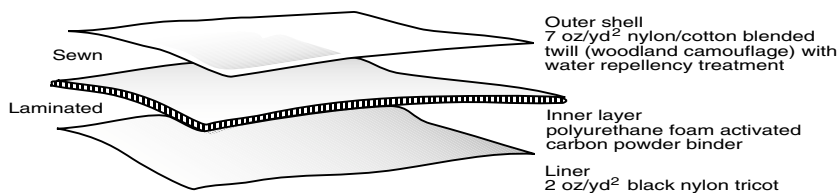polyurethane foam activated carbon powder binder

Liner
2 oz/yd² black nylon tricot

FIGURE B-2 Components of a typical barrier system.

TABLE B-4 Summary of Required Improvements in Material Properties

Needs	Properties
Decreased weight	Decreased fiber specific gravity Decreased packing density
Decreased bulk	Decreased fiber diameter Increased packing density
Increased durability	Increased strength, toughness
Increased comfort	Increased permeability
Decreased heat stress	Increased thermal conductivity

Source: Ko, 1999.

(2) selectively permeable/membrane materials. The sorptive layer involves using activated carbon (powder or fibers) to adsorb agent. Carbon powder can be in the form of foam, coated fibers, hollow fibers, or melt-blown fibers. Activated carbon fibers can be used as nonwoven, flocked fabrics or laminated structures. Chemical decomposition of agents can be achieved through the use of reactive resins or reactive enzymes. The selective permeable/membrane concept is the focus of current R&D by SBCCOM's Soldier Systems Center (Figure B-3).

The current standard U.S. Army chemical protective BDO has the following configuration: the outer shell consists of 7 oz/yd^2 nylon/cotton blended twill (woodland camouflage) or around 6 oz/yd^2 triblend (cotton/nylon/Kevlar) twill (desert camouflage) with water repellent treatment. The inner layer contains the activated carbon impregnated into approximately a 90-mil polyurethane foam laminated to a 2 oz/yd^2 nylon tricot liner. The inner layer components are laminated together. The top layer essentially floats and is put on as the garment is manufactured.

The aircrew uniform integrated battlefield (AUIB) combines CB protection with flame resistance with an outer shell made of 95 percent Nomex and 5 percent Kevlar. The inner layer is similar to the inner layer of the BDO. Clothing used by the Marine Corps, the Saratoga, is a CB protective suit with carbon sphere. An alternative to the BDO, the Saratoga can be worn over normal duty uniforms.

The JSLIST Program was completed recently and is currently progressing to the JLIST P3I. The purpose of these programs was to develop the next generation of chemical protective clothing ensembles by consolidating ongoing efforts: (1) to provide the best suit(s) possible for each service (Air Force, Army, Marines, and Navy); (2) to minimize the types
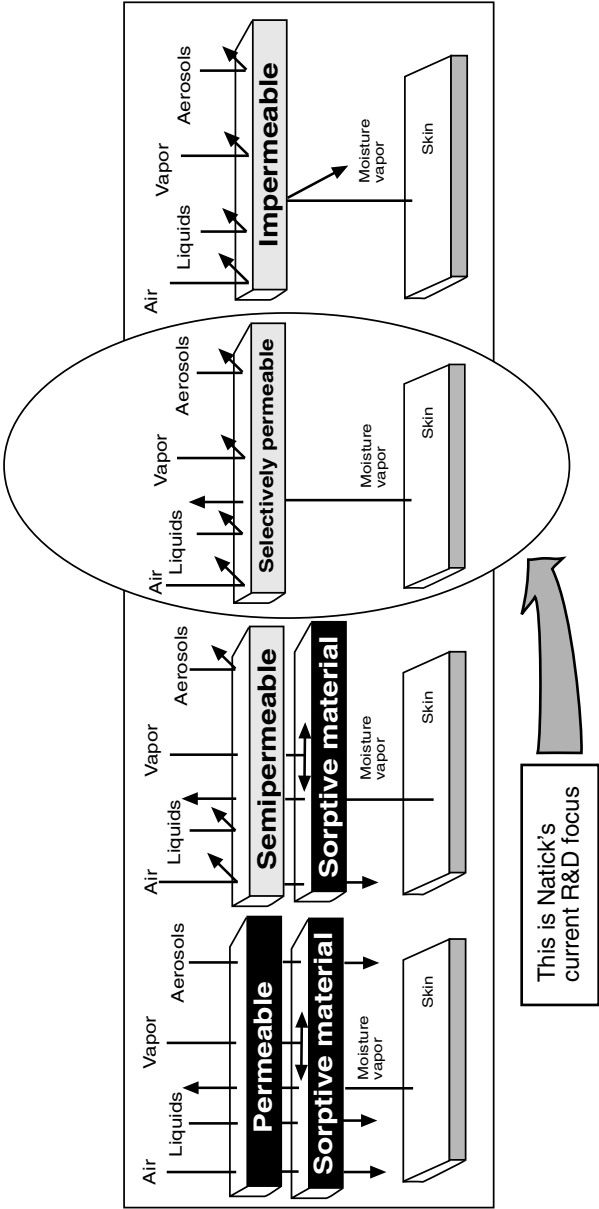
FIGURE B-3 Selectively semipermeable barrier construction. Source: *Wilusz, 1998.*

of suits in service; (3) to maximize economies of scale; and (4) to conserve service resources.

The JSLIST overgarment is a universal, lightweight, two-piece, front-opening garment that can be worn as an overgarment or as a primary uniform over personal underwear. It has an integral hood, bellows-type sockets, high-waist trousers, adjustable suspenders, adjustable waistband, and waist-length jacket. This overgarment is more comfortable and more readily accepted and is compatible with other equipment.

The JSLIST overgarment provides optimum protection against vapor and aerosol agents, as well as liquid resistance. It is fully compatible with the extreme cold weather clothing system; the improved chemical and biological protective gloves; the multipurpose overboot; the M17, M40, M43, and MCU2P series protective masks; protective masks currently under development, including the XM45; clothing and individual equipment; and developmental individual soldier and marine systems, including the next-generation family of body armor, Generation 11 systems, and Land Warrior systems. The key features of the JSLIST overgarment include: CB agent protection; reduced heat stress; launderability; enhanced durability; improved capability; and improved comfort (Barrett, 1998).

The system is now available in several different configurations through the United States licensee, Tex-Shield, Inc. The Saratoga system, which uses encapsulated active-carbon spheres, has demonstrated lower heat stress, higher air permeability, repeated laundering, resistance to perspiration and petroleum products, nonflammability, good strength, and less bulk (Gander, 1997).

An integral part of the development of chemical protective clothing is the development of testing and evaluation methods for assessing the performance of chemical protective clothing under simulated conditions that are as realistic as possible. Tests for evaluating the effectiveness of barrier systems vary from simple small-scale swatch tests to full-scale field tests (NRC, 1997).

TEXTILE MATERIALS

Fibers

Textile fibers are slender, flexible, and have a length-to-diameter ratio of 1,000:1. Beside flexibility, the unique characteristic of textile fibers is a combination of strength, light weight, and toughness. The strength of fibers ranges from 1 gram per denier (g/den) to 40 g/den for super high-strength fibers. Elongation ranges from 1 percent to several hundred percent for elastomers.
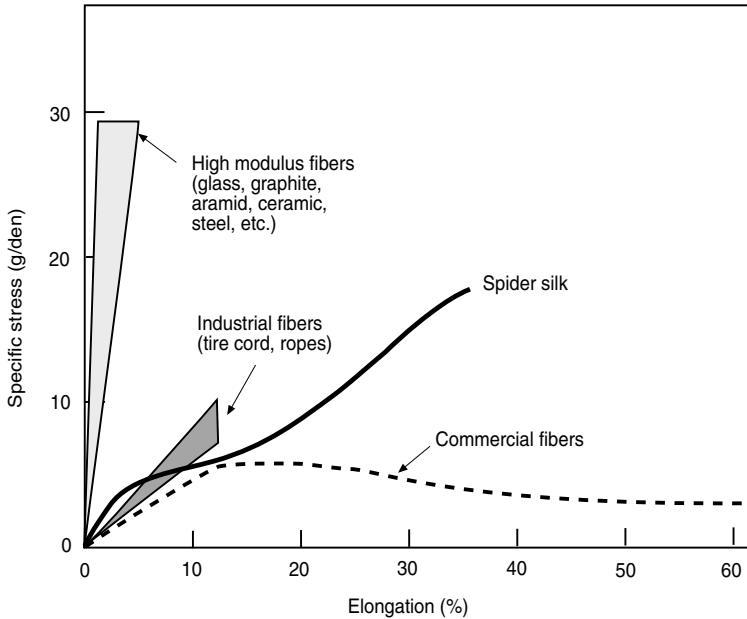
FIGURE B-4 Stress-strain curves of natural and man-made fibers. Source: Ko, 1999.

The stress-strain properties of fibers depend on their chemical composition and internal structures. The stress-strain curves of natural and man-made fibers show the wide range of material properties available (Figure B-4). The fiber with the best combination of strength and toughness is spider silk. Therefore, spider silk has been selected as the model for the fiber of the future for soldier protection. Textile fibers are classified according to their geometry, chemical composition, or thermomechanical properties (Table B-5).

Natural fibers include wool, silk, and asbestos; man-made fibers include rayon, aramid, and graphite. Fibers may be categorized as organic or inorganic on the basis of their hydrocarbon composition. Most general-purpose textile fibers are organic; most high-performance fibers are inorganic. Thermoplastic and thermoset fibers are defined based on their response to temperature. Thermoplastic fibers, such as polyester or nylon, can be formed and reshaped under temperatures higher than their solidification, or setting, temperatures. Thermoset, such as rayon and epoxy-based fibers, once set, cannot be changed. Fibers are classified as regular,

TABLE B-5 Physical and Mechanical Properties of Textile Fibers

Fiber	Density (g/cc)	Strength (g/denier)	Modulus (g/denier)	Elongation (%)	Melting Temp (°C)	Moisture Regain (%)
Polypropylene	0.90	3.5	20.0	70.0	160	0.01
Polyethylene (Spectra)	0.97	30.0	1400.0	3.6	143	0
Nylon	1.14	3.5	17.0	16.0	248	4.0
Modacrylic	1.18	1.7	3.8	45.0	(198)	2.5
Wool	1.31	1.0	4.5	25.0	(298)	16.0
Polyester	1.38	2.8	12.0	12.0	250	0.4
Aramid (Kevlar 29)	1.44	23.0	500.0	4.0	(482)	4.3
Rayon	1.52	2.3	60.0	10.0	(176)	
Cotton	1.54	3.0	60.0	3.0	(149)	8.5
Carbon	1.78	24.0	1,500.0	1.6	N/A	N/A
Teflon	2.2	0.9	1.0	19.0	326	0
E-glass	2.54	15.3	320.0	4.8	1,120	0

Source: Ko and Song, 1996.

medium, high, or super-high tenacity according to their responses to tensile loading.

General Properties of Fibers

The structure and properties of textile fibers have been the subject of several books over the past 40 years. The first treatment of fibers as an engineering material was presented by Dewitt Smith in his ATSM Edgar Marburg Lecture (DeWitt Smith, 1944). As the development of synthetic fibers continued, Harris and his associates at the Harris Research Laboratories compiled an impressive collection of physical and mechanical properties of textile fibers (Harris, 1954). Moncrieff (1963) gave a comprehensive description of the function of commercial fibers emphasizing the technological, experimental, and economic aspects of fiber development. Herman Mark et al. (1967) edited a three-volume treatise on man-made fibers. Expanding on the 1962 edition of their book, Morton and Hearle (1975) published a textbook on the physical properties of textile fibers representing the most up-to-date discussion of the structure, properties, and characterization of fibers.

Physical Properties of Conventional Textile Fibers

Thermal Properties

Thermal properties include melting temperature, softening temperature, and decomposition temperature. These properties indicate how well a fiber can withstand the temperature for use. As a general textile, it should have a melting point higher than 200°C. Melting temperatures range from 140°C for polypropylene to 800°C for glass to 3,600°C for graphite.

Moisture Absorption

The water absorption characteristics of fibers are usually expressed in terms of moisture regain. Because the moisture content of fibers affects the weight, moisture regain is an important consideration for fiber users. Moisture in a fiber also affects its mechanical properties, comfort, and processability. Hydrophilic fibers absorb water readily; hydrophobic fibers absorb little or no water. Moisture regain is computed by the following equation:

$$mosture\ regain = \frac{conditioned\ weight - dry\ weight}{dry\ weight} \times 100\%$$

The amount of moisture a fiber absorbs depends on the presence of polar groups and the availability of these groups within the amorphous regions of the fiber. The principal water-binding groups in fibers include the hydroxyl, carboxyl, carbonyl, and amino groups. Natural cellulosic fibers are usually more hydrophilic than synthetic fibers. Moisture regain ranges from 0 percent for hydrophobic fibers like glass and polypropylene to 16 percent for hydrophilic fibers like wool.

Electrical Properties

The electrical resistance of a fiber depends on the humidity of the atmosphere and the nature of the polymer. Fibers of high electrical resistance are prone to "static" problems. The generation of static electricity causes difficulty in textile processes, such as yarn spinning, weaving, and knitting. Static also causes garments to cling and makes soil removal difficult in laundering and dry cleaning. Cellulosic fibers have low electrical resistance; synthetic fibers have high electrical resistance. Electrical resistance ranges from 6.8 Ω kg/m^2 (ohm kilogram per square meter) for cotton to 14 Ω kg/m^2 for polyester and acrylic.

Fiber Geometry

The surface geometry of fibers can be characterized by roughness, cross-sectional shape, and crimp. Surface geometry affects the frictional characteristics, luster, bulkiness, and flexibility of a fiber. Fiber geometry affects the appearance of textile structures, the processability of fibers, and the handling and mechanical properties of fabrics. Most natural fibers have rough surfaces and irregular cross-sectional shape and crimp. The cross-sectional shape of synthetic fibers ranges from round to irregular; the cross-sectional shape of some fibers can be modified to change their working characteristics. Delustrants are usually added to increase the surface roughness of synthetic fibers.

The fineness of the fiber has the most influence on the performance of CB protective textiles. Fiber diameters range from 20–26 microns for wool to 0.001 microns for electrospun fibers (Fukuhara, 1993). Microfibers can be produced by drawing, islands-in-the-sea (when a particular fiber contains individual smaller fibers of one polymer spun inside a matrix, or sea, of another fiber), radial sheath separation, or multilayer separate processes. Toray (a leading Japanese producer) has reported that fiber diameters as fine as 0.1 micron (0.0001 denier) have been successfully produced in the laboratory (Fukuhara, 1993). Recently, du Pont also introduced a textile microfiber. Most microfibers are for garment applications.

A microdenier carbon fiber (Pyrograf) produced by GM by the vapor-grown process has a diameter of 0.2 microns, which increases the available fiber surface. The finest fibers that have been demonstrated, however, are produced by the electrospinning process. In this process, a polymer solution is exposed to an electrical field that elongates the polymer jet to form fibers ranging from 50 to 150 nm in diameter (Reneker and Chun, 1996). A wide range of polymers have been demonstrated successfully in Dr. Reneker's laboratory at Akron, at the Fibrous Materials Research Center at Drexel University, and at several government laboratories (Gibson et al., 1999; Ko et al., 1998).

Different functionalities can be introduced to the fibers (i.e., activated carbon imbedded fibers, hollow fibers filled with activated carbon, activated carbon overbraided with cotton, activated carbon-coated yarns, and reactive fibers) by texturing, polymer modification, special sizing, denier mixing, sludge mixing, coating, wrapping, and chemical treatment. The combination of nanofiber with microfiber or regular multifilament fibers is a new program being initiated in the Drexel-Akron part of the Army MURI program. A wide range of bulkiness and mechanical properties can be engineered into a fiber.

Yarns

A yarn is a continuous strand of textile fiber or filaments in a form suitable for knitting, weaving, or intertwining to form textile fabrics. The formation system depends on the nature of the fiber (natural or man-made; long or short; fine or coarse) and the end-use requirements. The fiber material properties and the geometry (e.g., twist, denier, etc.) determine the performance properties of a yarn and consequently, dictate the processing methods and applications for which a yarn is suited. For the implemented technology of yarns, readers are encouraged to consult Goswami et al. (1971) and Kaswell (1965). Yarns can be classified according to form, by formation system, or by physical properties and performance characteristics.

State of the Art of Fibers and Yarns

The fiber and textile industries have made a good deal of progress in the production of fibers and yarns, especially in Japan and Europe whose textile machine industries dominate the world market (Berkowitch, 1996). The following excerpts from Berkowitch's review describe advances in Japanese industry.

Driven by the desire to lower cost and increase uniformity of synthetic fibers, eight producers participated in a six-year MITI funded project that ended in 1988. The project was designed, among other things, to raise polyester spinning speed beyond 6,000 m per minute. …these advances resulted in an abundant patent literature and lowered the rate of yarn breaks by a factor of 100 (down to 1 or 2 per 10^8 m), making it possible to operate continuously at 6,000 m per minute for 12 days. They allow easy spinning in the range of 6,000 to 8,000 m per minute. The participating producers incidentally designed and built most of the equipment required for the improvements, including winders.

As a result of the project, producers now can use either a pressurized compartment or a compressed air circulation arrangement to sequentially draw and false-twist texture polyesters at wind-up speeds exceeding 2,000 m per minute.

Still another outcome of the MITI project was the clustered spinning of several (three to ten) yarn ends into a single spinning block. Circular air flow delivered perpendicularly to the spinning direction quenches the bundles of filaments, which may range from 0.8 to 8 deniers. Winding takes place at speeds anywhere from 3,000 to 8,000 m per minute.

Today, automation of the spinning process has reduced the amount of labor to the point where major producers have essentially unmanned polyester and nylon production lines.

Berkowitch goes on to predict that Korean industry is following suit. Another innovation in Japanese industry is flexibility in manufacturing systems.

The growth of the specialty fiber business prompted producers to increase the flexibility of their facilities. Streams of homopolyester coming from continuous polymerizers are now split into substreams, each modified by injecting additives, such as pigments, lubricants, and hydrophilic and antimicrobial agents, and each homogenized with in-line static mixers to produce parallel yarn ends of different compositions in small volumes.

The review of conjugate-spun products outlined the spinning of filaments that contain two or more distinct polymer phases. Once in fabrics, the yarns are subjected to one of four finishing procedures, depending on their composition and targeted end use. The first, heat setting after bleaching and dyeing, does not alter the macrostructure of the filaments. It only stabilizes the dimensions of the fabric, which has the attributes brought about by the additive used in one of the two polymer phases. The second, heat relaxation, lets the individual filaments self-crimp according to the asymmetry and difference of shrinkage

potential that exists between the two phases. It also confers stretch. The third, generally an alkaline treatment, dissolves one of the phases freeing the other. The fourth, mechanical fibrillation, subdivides the filaments longitudinally, capitalizing on a designed low-phase adhesion. The last two produce sub-denier filaments, leading to novel aesthetics and functionalities.

The cross-section geometry of a conjugate-spun filament mirrors the shape, size, and relative position of the small orifices from which the various polymer streams emerge immediately prior to their coalescence. The range of numerical values these variables can take, not to mention the diversity of polymer compositions, opens the door to a practically unlimited number of combinations and thus products.

Berkowitch also described fluid-based processing techniques.

Fluid-processing techniques (air, steam, or water) are broadly found in textiles worldwide as substitutes for mechanical devices offering high productivity and labor savings. The turbulence created by impinging products with fluids alters their structures in a desirable way. This action takes place inside jets, as with air in consolidating filament bundles by interlacing; bulking yarns by crimping and looping; or forming staple yarns by entangling and wrapping. In another series of embodiments, pressurized water exiting from jets generates subdenier filaments by fibrillation), forms nonwoven fabrics by fiber lacing, and propels fill yarns across warps on waterjet looms.

One Japanese textile equipment manufacturer pioneered a staple yarn formation process that uses two air-driven torque jets operating in series, but with the directions of their vortices opposite to each other. Fabrics made from such yarns tend to have a harsh hand and, for that reason, have been frowned on by the domestic market. However, other countries (the United States in particular), driven by the attractive economics, have commercialized the process and continue to seek improvements by fine-tuning feed fiber specifications. With growing cost sensitization, the Japanese textile industry may soon start adding to the 2,500 machines already in use abroad.

Fabrics

Although there are numerous possibilities for fabric geometries, most fabrics are formed by the three basic systems: (1) weaving (interlacing two or more systems of yarns); (2) knitting (interlooping one or more yarns); (3) chemical or mechanical bonding of fibers for nonwoven fabrics. As a rule of thumb, knitting is approximately 10 times faster than weaving, and nonwoven fabrics can be made about 100 times faster than woven fabrics.

Fabric Performance Characteristics

Fabric performance characteristics are based on the interaction between fiber (material properties), yarn, fabric geometry, and finishing treatment. Obvious characteristics of fabrics for textile applications are: (1) comfort; (2) aesthetic value; (3) functionality and durability; and (4) ease of care.

Garments

The garments and protective textile structures for the soldier are produced by direct fiber-to-fabric or yarn-to-fiber processes. Yarn-to-fabric structures include woven and knitted fabrics. Fiber-to-fabric structures are known as nonwoven structures. A wide variety of fiber architectures can be generated from the three basic fabric processes (weaving, knitting, and bonding), resulting in a wide range of interlacing (bonding) density, fiber orientation/distribution, and formability/conformability. For example, woven fabrics include biaxial, triaxial, and multiaxial interlacing of yarns; and interlacing density varies from high density in the plain weave construction to low density in the satin weave construction. Knitted structures (interlooped structures) are characterized by high porosity and conformability. Knits are classified into warp knits (yarns are introduced across the machine) and weft knits (yarns are introduced along the machine). The openness of knitted structures can be reduced and the stability of the structure enhanced by the insertion of directional yarn. Inserted yarns can be organized from unidirectional, orthogonal, and bidirectional to multidirectional.

Nonwoven structures are primarily formed by direct conversion of fiber-to-fabric by mechanical or chemical bonding. These fiber-based structures are characterized by high areal coverage to areal density ratio. Nonwoven fabrics are extremely versatile because they can combine fiber-based and yarn-based structures. Mechanically bonded nonwoven fabrics can be produced by needling or fluid-jet entanglement. These structures tend to be bulky but quite conformable. Chemically bonded nonwoven fabrics are less bulky but tend to be paper-like and nonconformable. Because of the simplicity of processing and high productivity of nonwoven fabrics, industry has a strong incentive to use nonwoven structures for primary garment fabrics. However, their paper-like consistency has been a major obstacle to the popular acceptance of nonwoven structures.

The current JSLIST garment is a combination of all three textile structures. Woven structures are used in the shell; the liner is warp knitted; and the structure that carries the activated carbon absorbents is a nonwoven fabric (or foam).

Automated Garment Manufacturing

The automation of garment manufacturing in the United States is well behind that of Japan. Complete automation of the tailored apparel manufacturing system was developed in Japan under a nine year Ministry of International Trade and Industry funded contract begun in 1982. According to Berkowitch (1996):

> A consortium of 28 enterprises from all segments of the industry cooperated in the project. The seed for the initiative lay in the uncertain future faced by a labor-intensive, low-tech industry in a high-wage economy and in the potential for a domestic production capability that had low labor requirements and was flexible, just in time, and quality oriented. The undertaking was ambitious—it called for having a bolt of cloth at one end and tailored garments ready for shipment at the other, without the intervention of human hands in between. It anticipated that manufacturing time would be cut in half. Technically, the challenge was to apply robotics to the manufacture of sophisticated sewn articles using diverse flexible materials. By the time the project concluded in 1990, essentially all process elements had been demonstrated in the production of tailored women's jackets of woven and knit cloths, patterned and dyed in solid colors.

In the future, individual modules of the production line optimized for making specific garments or garment parts are likely to find their way into the domestic industry in Japan.

Fabric Performance Maps

The properties of textile structures can be characterized in terms of geometric and performance properties critical to CB protection. The performance maps outline the region of performance of various fabrics. To facilitate comparisons on the same basis, the fabric performance maps for yarn-to-fabric and fiber-to-fabric structures are discussed separately. Because of the broad range of possibilities, the performance maps are qualitative, rather than quantitative.

Critical Properties

The properties included in the performance maps reflect the basic requirements of CB protective textiles: (1) reduction in weight; (2) reduction in bulk; (3) reduction of heat stress (increased comfort); and (4) increased durability. These requirements can be translated into four geometric parameters and four performance parameters. The geometric parameters include:

- *Porosity* (the amount of open space in a unit volume of fabric). As fiber diameter and yarn diameter increase, the structure tends to become more porous. The porosity of a fabric is inversely proportional to the areal coverage or cover factor of a fabric. A porous fabric tends to be lighter and more permeable than a nonporous fabric.
- *Surface Texture.* The surface geometry of a fabric is characterized by the smoothness of the surface, which in turn is governed by fiber and yarn diameter.
- *Voluminosity* (a reflection of the bulkiness of a fabric for a given areal density [mass per unit area]). A fabric tends to be more voluminous if the fiber/yarn diameter is larger and the freedom of fiber mobility in the geometric repeating unit is high. Voluminosity is directly related to fiber thickness.
- *Thickness of the fabric*. Like voluminosity, thickness is related to fiber and yarn diameter. The larger the fiber and yarn diameter, the thicker and bulkier the fabric.

The performance parameters include:

- *Permeability* (the ease of air or liquid flow through a fabric). The permeability of a fabric increases when the porosity increases.
- *Compressibility* (the ability of a fabric to resist transverse [through the thickness] compression). A voluminous fabric tends to be more compressible than a nonvoluminous fabric. Compressibility decreases with the stiffness of the fiber and yarn, which is significantly influenced by fiber diameter. As fiber diameter increases, the bending stiffness and longitudinal compressive stiffness of the fiber increases geometrically.
- *Extensibility* (the ability of a fabric to stretch and conform). Fabric extensibility is affected by fabric geometry and inherent fiber bending elongation.
- *Toughness* (the durability of the fabric). A high-strength fabric with high elongation at break usually has high toughness.

Yarn-to-Fabric Structures

Interlooped structures, such as weft knits, tend to be more porous, more voluminous, and bulkier and thicker than other yarn-to-fabric structures. Interlaced structures, such as woven fabrics, tend to be less porous, less bulky, and thinner. The performance of all yarn-to-fabric structures is largely determined by the linearity and interlacing density of the yarns. For example, weft knits have high extensibility, are extremely comfort-

able, and are very compressible. Because of the openness of the loop geometry, weft knits are highly permeable. Because of the high linearity of the multiaxial (noncrimped) warp knit structure, these fabrics have limited extensibility and low toughness. The permeabilities of woven and multiaxial warp knit fabrics are lower than those of weft knit fabrics. Figures B-5 and B-6 show the qualitative performance maps for the geometric and performance properties of the yarn and fabric.

Fiber-to-Fabric Structures

Fiber-to-fabric structures are generally known as nonwoven fabrics. The simplicity of the manufacturing processes by which fibers are converted directly to fabrics (thus bypassing the yarn-formation stage) has great appeal to the industry (especially the apparel industry) because of high productivity and cost savings. But nonwoven fabrics do not have good drapability/conformability characteristics. Of the two major classes of nonwoven fabrics (chemically bonded and mechanically bonded), mechanically bonded systems (e.g., needle felts and spunlaced systems) tend to be more voluminous, bulkier, thicker, and more porous. Chemically bonded nonwoven fabrics tend to be more paper-like, thin, nonbulky, and less porous. As a result, mechanically bonded nonwoven fabrics are more permeable, more extensible, and more compressible.

The performance map shows only a partial view of the toughness of nonwoven fabrics. A spun-bonded system, because of the high strength of the continuous filaments and the strength of the bonds, has a high level of shear resistance, tear resistance, and toughness. The needle felt fiber (e.g., Kevlar), can also be quite tough, even capable of arresting fragments from a ballistic projectile.

A summary of the performance map of fiber-to-fabric structures is shown in Figures B-7 and B-8. The effect of fiber orientation (fiber architecture) on permeability is illustrated in Figure B-9. Nonwoven fabric, because of its torturous fiber architecture, is significantly less permeable than woven fabric under the same fiber volume fraction. In nonwoven fabrics, fiber dimension engineering can further modify coverage or porosity. Finer fibers provide significantly higher fabric coverage (Ko and Pastore, 1985). Based on the general performance map, experimental evidence, and simulated results, we can conclude that fiber architecture and fiber diameter are very important in controlling the geometric and performance characteristics important for CB protective textiles.

FUTURE DIRECTIONS

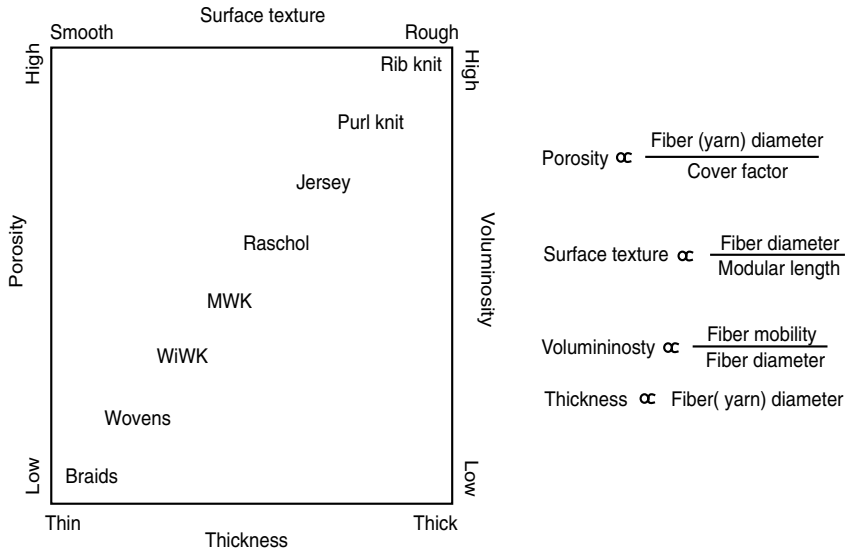The requirements for the next generation of CB protective garments

Surface texture

Smooth   Rough

Porosity $\propto \dfrac{\text{Fiber (yarn) diameter}}{\text{Cover factor}}$

Surface texture $\propto \dfrac{\text{Fiber diameter}}{\text{Modular length}}$

Volumininosty $\propto \dfrac{\text{Fiber mobility}}{\text{Fiber diameter}}$

Thickness $\propto$ Fiber(yarn) diameter

FIGURE B-5 Geometric properties of knit and woven fibers. Source: Ko and Song, 1996.

Compressibility

Low   High

Permeability $\propto \dfrac{\text{Fiber diameter}}{\text{Fiber volume fraction}}$

Compressability $\propto \dfrac{\text{Voluminosity}}{\text{Fiber stiffness}}$

Extensibility $\propto \dfrac{\text{Fiber elongation}}{\text{Yarn linearity}}$

Toughness $\propto \dfrac{\text{Strength} \times \text{elongation}}{\text{Stiffness}}$
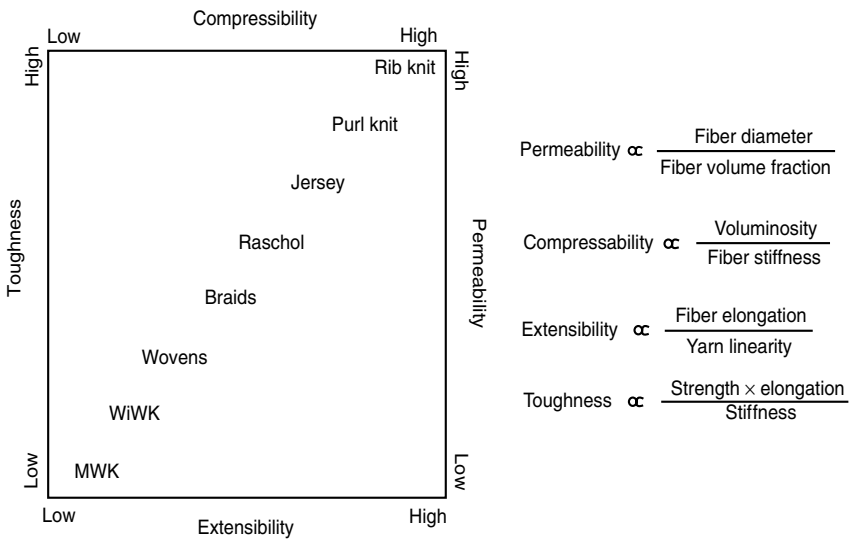
FIGURE B-6 Performance properties of knit and woven fibers. Source: Ko and Song, 1996.

Surface texture

Smooth — Rough

High — High

Needle felt

Spunlaced

$Porosity \propto \dfrac{Fiber\ (yarn)\ diameter}{Cover\ factor}$

Porosity

Voluminosity

$Surface\ texture \propto \dfrac{Fiber\ diameter}{Modular\ length}$

Spunbonded

$Voluminosity \propto \dfrac{Fiber\ mobility}{Fiber\ diameter}$

Resin bonded

$Thickness \propto Fiber(\ yarn)\ diameter$

Film/membrane

Low — Low

Thin — Thick

Thickness
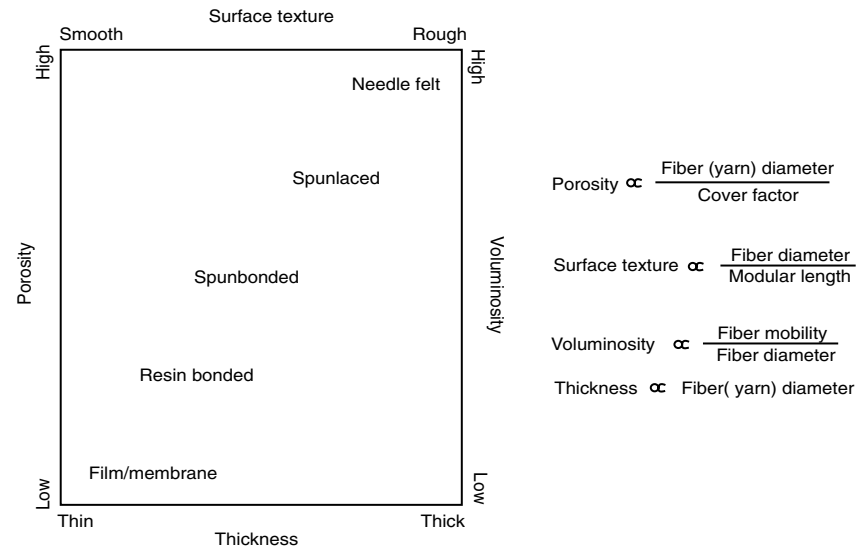
FIGURE B-7 Geometric properties of nonwoven fibers. Source: Ko and Song, 1996.

Compressibility

Low — High

High — High

Needle felt

Spunlaced

$Permeability \propto \dfrac{Fiber\ diameter}{Fiber\ volume\ fraction}$

Toughness

Permeability

Spunbonded

$Compressability \propto \dfrac{Voluminosity}{Fiber\ stiffness}$

$Extensibility \propto \dfrac{Fiber\ elongation}{Yarn\ linearity}$

Resin bonded

$Thickness \propto \dfrac{Strength \times elongation}{Stiffness}$

Film
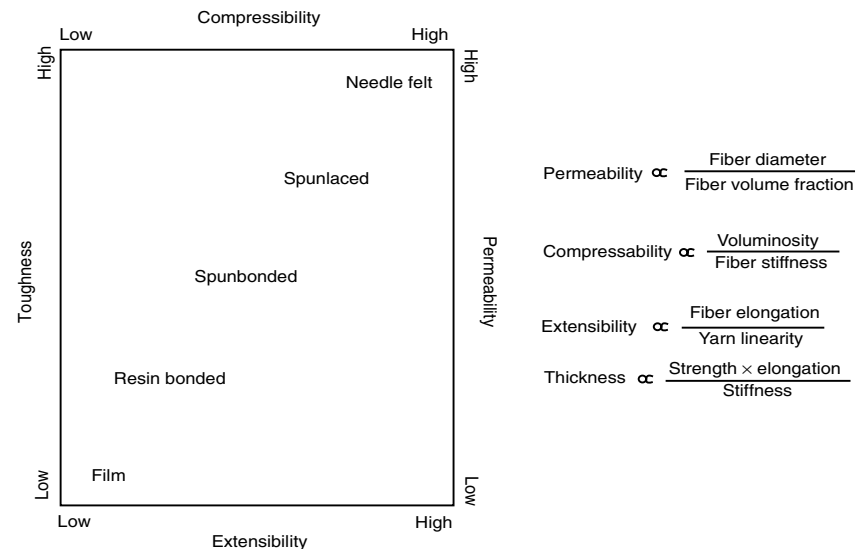
Low — Low

Low — High

Extensibility

FIGURE B-8 Performance properties of nonwoven fibers. Source: Ko and Song, 1996.

For yarn in general, low permeability to
air, vapor and light dictate;
1) High circularity coefficient for the
    component fibers;
2) Surface smoothness for the component
    fibers;
3) Low state of aggregation (packing factor)
    achieved, for example, by utilizing
    multiplanner crimp fibers and low twist.

For fabric in general, maximum
translation of yarn properties for low
permeability requires:
1) Low number of yarns per unit length and
    width of fabric;
2) Low cover factor factor-warp and filling;
3) High crimp level-warp and filling;
4) Maintenance of yarn circularity
5) Weave types containing the minimum
    number of continuous intersections.

High permeability requires essentially the
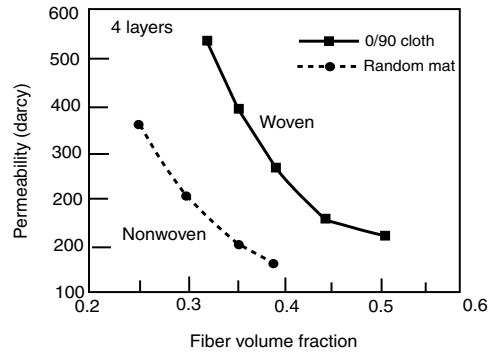converse of these characteristics.

FIGURE B-9 Effects of fiber orientation on permeability. Source: Ko and Song, 1996.

have not been quantified or defined. New analytical methods will have to be developed for the new classes of fibrous materials and structures. Multifunctional materials will require special function polymeric fibers and hybrid yarns consisting of two or more polymers and their ultrafine filament derivatives. Yarns and fabrics consisting of the ultrafine fibers will require sophisticated processing and finishing techniques. The unique surface texture and multifunctional nature of these new textiles will require computer-aided design and manufacturing for reproducibility and flexible manufacturing for meeting mission-specific demands. The production economics will require high-speed, automated processes, including fiber spinning, fabric formation, printing (camouflage), and garment manufacturing. The capability of the U.S. defense industry to develop and field advanced CB protective textiles and garments will require the cooperative participation of research institutions as well as the fiber-textile-garment industry.

CONCLUSIONS

It is generally accepted that the impermeable system provides the most complete protection against CB agents, whereas the permeable system, which breathes and allows moisture vapor to escape, cannot protect against aerosol and liquid agents (Wilusz, 1998). Impermeable barriers, however, cause serious heat stress by trapping bodily moisture vapor inside the system. An incremental improvement can be achieved using a semipermeable barrier backed with a sorptive layer. This system allows

TABLE B-6 Trends In Chemical/Biological Protective Textiles

	Current	Future
Fiber material	Monofunctional	Multifunctional
Fiber geometry (diameter)	Micro >10µm	Nano <µm → nm
Fiber architecture (fabric)	Woven (yarn-to-fabric)	Nonwoven (hybrid) (fiber-to-fabric)
Garment manufacturing	Cut and sew labor intensive	Net shape, seamless automation, flexible manufacturing
Garment design	Skill based, sequential	Concurrent engineering, integrated
Characterization	Test and try	Continuous monitoring

Source: Ko, 1999.

the moisture vapor from the body to escape; however, air can still penetrate, and the system is both bulky and heavy.

An obvious solution would be ultrafine fibers (i.e., nanofibers or microfibers) for the membranes that could be selectively permeable. If one decreases the diameter to the nanoscale, the pore size of the membrane is reduced, and the available surface area is increased significantly. The strength of nanofiber fibers, however, is still far below that of conventional textile fibers. In addition, the technology of processing nanofibers in traditional textile machines is not well established. Neither the dynamic interaction between nanofibers and machine surfaces nor the problems that will be encountered in chemical and mechanical finishing of fabrics containing nanofibers (e.g., snagging, adhesion, melting, agglomeration) have been investigated.

The sewing process creates easy pathways for agent penetration. Therefore, the manipulation, transportation, and assembly of the protective garments must be carefully planned, whether the garment is made manually or automatically. A summary of the future directions in CB protective textile materials and technologies is presented in Table B-6.

A recent observation by Berkowitch (1996) describes the different approaches of the textile and apparel industries in the United States and Japan:

> The U.S. apparel industry's…strategy is driven mainly by cost, with yield, speed, and product uniformity at the top of its agenda and new

process development drastically reduced. Having gradually lost its equipment manufacturing segment, it relies on developments from foreign manufacturers for process modernization. The attention given to quality bears primarily on uniformity and processibility. Introduction of product variants is kept to a minimum and frequently prompted by pressure from imports in the lower half of the market. The mills have not been challenged by the specialty products covered in this report. These products are practically unavailable here because the currency exchange rate makes them exorbitantly expensive. The situation would likely change, though, were their prices to drop as a result of offshore manufacturing. Development of specialty products based on novel concepts has also been curtailed on the assumption that the U.S. consumer would not support the premium. The industry clearly continues to aim at a volume business and shows reluctance to diversify. Further evidence of this reluctance is found in the industry's phaseout of mid- and long-range research and in the focus of its limited technical resources on existing businesses. Both steps emphasize the overriding importance of short-term payoff.

Japanese and American strategies thus differ, and the contrast has grown over the years. Indeed, several developments presented in this report originated in the United States. But, as time went on, the industry here turned its attention elsewhere, while the Japanese latched onto the trends and improved on them. Time will tell which of the two will prevail in the barrier-free, fiercely cost- and quality-competitive world. . .

As these trends continue, the U.S. textile and garment industry will be dependent on foreign textile materials and machinery technology. If we wish to assess the readiness of the U.S. textile-garment industry to meet the CB protective textile and garment requirements, we must ask several questions. Do we have the necessary multifunctional fiber materials? Do we have the necessary specialty, ultrafine fiber, yarn, and fabric processing technologies? Do we have quick-response garment manufacturing technologies that can meet changing needs? Unfortunately, the answer to all of these questions is no.

Recognizing that U.S. industry is not prepared at the material or technological level to respond to the need for a selectively permeable uniform for the soldiers, the Department of Defense has taken the initiative by supporting R&D at universities and industry. Rapid advances in nanotechnology and biotechnology should stimulate the development of new material and processing concepts. New engineering design tools and manufacturing technologies will be necessary, however, for these innovative concepts to be translated into product realities.

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